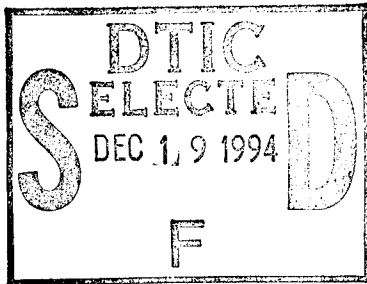Serial No. <u>269,278</u>

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HIGH POWER, BROADBAND FOLDED WAVEGUIDE
GYROTRON-TRAVELING-WAVE-AMPLIFIER

Background of the Invention

1.   Field of the Invention

The present invention relates generally to gyrotron-traveling-wave-amplifiers and particularly to a folded waveguide, gyrotron-traveling-wave-amplifier capable of producing high power, broadband millimeter wave radiation.

2.   Description of the Related Art

Broadening the instantaneous bandwidth (BW >10%) of high power millimeter wave amplifiers remains a critical issue in high power vacuum electronics. Light weight, compactness and low-cost are also important factors to be met for both practical military and commercial applications. Military applications include high resolution radar/communications and electronic jamming equipments. Commercial applications include navigation equipments for airborne and ship-board systems, high efficiency satellite communication systems, low-cost millimeter-wave material processing, millimeter wave imaging systems, and RF test and measurements.

Use of free electron beams (linear beam and rotating beam) in vacuum tubes has been recognized as a promising source of multi-kilowatt high power, broadband millimeter wave radiation,

1   operating at a moderate beam voltage (< 60 kV). Uniform

2   waveguide gyro-amplifiers cannot produce an instantaneous

3   bandwidth in excess of 10%, unless the waveguide is loaded so

4   that the wave phase velocity becomes constant over a wide

5   frequency range. Conventional approaches for achieving wideband

6   (BW > 10%) RF amplification in gyrotron-traveling-wave-amplifiers

7   are either loading disks or dielectric in the waveguide to slow

8   down the RF phase velocity of the wave or tapering both the

9   waveguide and the external magnetic field along the axial

10   distance. Since the azimuthal and axial beam modulations in the

11   beam-wave interaction of the conventional gyrotron-traveling-

12   wave-amplifier devices compete with each other, the operating

13   frequency band is either in the fast wave region (negative mass

14   instability) or in the slow wave region (Weibel instability).

15   This is one of the main limits to broadening the instantaneous

16   bandwidth. The present inventors do not know of any gyrotron-

17   traveling-wave-amplifiers in the prior art that can be operated

18   simultaneously in both the 'fast' and 'slow' wave regions,

19   continuously across the light line intersection.

20

21   Summary of the Invention

22   It is therefore an object of the invention to provide a

23   compact, low cost, gyrotron-traveling-wave-amplifier capable of

24   producing high power, broadband millimeter wave radiation.

1   Another object of the invention is to provide a

2 folded waveguide, gyrotron-traveling-wave-amplifier capable of

3 producing high power, broadband millimeter wave radiation.

4   Another object of the invention is to provide an H-plane

5 bend, serpentine waveguide amplifier.

6   Another object of the invention is to provide a double-

7 ridged, transverse electic, folded waveguide amplifier.

8   Another object of the invention is to provide a folded

9 waveguide gyrotron oscillator in a third embodiment of the

10 invention.

11   A further object of the invention is to provide an H-plane

12 bend rectangular serpentine waveguide in which an input axis-

13 encircling electron beam and an input RF millimeter wave

14 mutually interact with each other within the serpentine waveguide

15 to cause transverse beam modulation of the electron beam and RF

16 amplification of the RF signal and a broadening of the

17 instantaneous bandwidth of the amplified RF signal to occur by

18 way of the negative mass instability in the fundamental forward

19 space harmonic of both fast and slow wave regions.

20   These and other objects of this invention are achieved by

21 providing a folded waveguide gyrotron-traveling-wave-amplifier

22 for producing high power, broadband, millimeter wave radiation.

23 The invention includes an electron gun, an H-plane bend

24 serpentine rectangular waveguide having input and output ends,

1   and a beam collector in a first embodiment of the invention. In

2   operation, the electron gun injects an axis-encircling electron

3   beam through a beam tunnel hole of a narrow wall of the

4   serpentine rectangular waveguide. The injected electron beam is

5   modulated by the transverse electric field of an RF input signal

6   applied to the input end. The modulated electron beam amplifies

7   the RF input signal and broadens the instantaneous bandwidth of

8   the amplified RF signal input through the negative mass

9   instability in the fundamental forward space harmonic of both the

10   "fast" and "slow" wave regions. The amplified RF input signal is

11   outputted from the output end. In a second embodiment, a double-

12   ridged TE folded waveguide is used in place of the H-plane bend

13   serpentine waveguide. In a third embodiment, there is no RF

14   input signal and the interaction circuit generates an RF signal

15   which is outputted from one of the input and output ends.

16

17   Brief Description of the Drawings

18   These and other objects, features and advantages of the

19   invention, as well as the invention itself, will become better

20   understood by reference to the following detailed description

21   when considered in connection with the accompanying drawings

22   wherein like reference numerals designate identical or

23   corresponding parts throughout the several views and wherein:

24   Fig. 1 is a schematic diagram of a folded waveguide

1   gyrotron-traveling-wave-amplifier in a first embodiment of the

2   invention;

3   Fig. 2 is a graph of the dispersion diagram of the folded

4   waveguide gyrotron-traveling-wave-amplifier of Fig. 1;

5   Fig. 3 is a graph of signal gain versus frequency for the

6   rectangular folded waveguide gyrotron-traveling-wave-amplifier of

7   Fig. 1;

8   Fig. 4 is a graph of the output obtained from the use of the

9   MAGIC code, showing RF power growth along the axial distance

10   through the interaction circuit of Fig. 1;

11   Fig. 5 illustrates the equivalent circuit model of the

12   interaction circuit of Fig. 1, representing periodic bends and

13   periodic straight sections of the interaction circuit;

14   Fig. 6 illustrates numerical solutions of Fig. 5, showing

15   bandgaps near 32.2 GHz and 40.5 GHz;

16   Fig. 7 shows a multi-stage configuration of the embodiments

17   of Figs. 1 and 10;

18   Fig. 8 illustrates the effect of a beam tunnel hole on the

19   first bandgap of Fig. 6 and the center frequency shift of the

20   first bandgap from about 32.2 GHz to a lower frequency of about

21   31.5 GHz;

22   Fig. 9 is a graph showing the transmission loss through the

23   folded waveguide gyrotron-traveling-wave-amplifier of Fig. 1

24   obtained from the use of the MAGIC code;

1   Fig. 10 illustrates a double-ridged, transverse electric,

2   folded waveguide used in place of the folded rectangular

3   serpentine waveguide of Fig. 1 in a second embodiment of the

4   invention;

5   Fig. 11 illustrates a cross-sectional view of the double-

6   ridged, transverse electric, folded waveguide of Fig. 10;

7   Fig. 12 is a graph of signal gain versus frequency for the

8   double-ridged, transverse electric, folded waveguide of Figs. 10

9   and 11;

10   Fig. 13 illustrates a 12-period, single-stage test device of

11   the rectangular folded waveguide of Fig. 1;

12   Fig. 14 illustrates the return loss measured from the test

13   device of Fig. 13 under different conditions; and

14   Fig. 15 is a schematic diagram of a folded waveguide

15   gyrotron oscillator in a third embodiment of the invention.

16

17   Detailed Description of the Preferred Embodiments

18   Referring now to the drawings, Fig. 1 is a schematic diagram

19   of a folded waveguide gyrotron-traveling-wave-amplifier in a

20   first embodiment of the invention.

21   The folded waveguide gyrotron-traveling-wave-amplifier of

22   Fig. 1 is comprised of an electron beam source such as an

23   electron gun 21 for emitting a high-power axis-encircling

24   electron beam 23, an interaction circuit 25 and a beam collector

1   27. A magnet 29, such as a permanent magnet or an electromagnet,

2   develops a solenoid magnetic field around the interaction circuit

3   25 with an exemplary magnetic field strength of from about 1

4   Tesla to about 4 Tesla.

5   The interaction circuit 25 is an H-plane bend rectangular

6   serpentine waveguide 31 in which the orientation of the magnetic

7   field changes along the H-plane bend rectangular serpentine

8   waveguide 31. As is well known, this rectangular waveguide 31

9   has narrow and wide walls. The rectangular waveguide 31 includes

10   a first end 33, a second end 35 and a beam tunnel hole (not

11   shown) which passes through the narrow wall of the rectangular

12   waveguide 31. An input RF signal, having a preselected frequency

13   centered in a bandwidth or desired frequency range in a

14   preselected frequency domain and having a transverse electric

15   field, is applied to the first end 33 of the rectangular

16   waveguide 31 and propagates through the rectangular waveguide 31.

17   The high-power, axis-encircling electron beam 23 from the

18   electron gun 21 can be, for example, a 350 kW beam (a 70 kV, 5A

19   beam). This electron beam is injected through the beam tunnel

20   hole in the narrow wall of the rectangular waveguide 31. When

21   the electron beam passes through the narrow wall of the

22   rectangular waveguide 31 along a path 37 it has phase

23   synchronization with the RF phase velocity of the RF signal

24   propagating through the rectangular waveguide 31. Such phase

1   synchronization is produced because the interaction circuit 25

2   interacts with the RF phase velocity to slow the RF phase

3   velocity down so that the RF phase velocity becomes synchronized

4   with the electron beam velocity. In other words, the RF magetic

5   field changes its orientation around the bends of the H-plane

6   bend rectangular waveguide 31, so that the transverse electric

7   field can interact with the transverse momentum of the electron

8   beam 23.

9   Under this operational condition, the high-power axis-

10   encircling electron beam 23 exchanges energy with the transverse

11   electric field in the H-plane bend rectangular waveguide 31. As

12   a result, the injected electron beam 23 is modulated by the

13   transverse electric field of the RF signal. The modulated

14   electron beam 23 then amplifies the RF signal through the

15   negative mass instability in the fundamental forward space

16   harmonic of both the "fast" and "slow" wave regions in the

17   preselected frequency domain. The amplified RF signal is coupled

18   out of the second end 35 of the rectangular serpentine waveguide

19   31, while the remaining electron beam energy left after

20   interaction with the amplified RF signal propagates through the

21   beam tunnel hole in the rectangular waveguide 31 to the beam

22   collector 27.

23   The beam collector 27 is preferrably a depressed beam

24   collector. A depressed collector is a beam collector 27 which has

1   a preselected negative voltage applied to it (but less negative

2   than the negative potential of the electron beam from the

3   electron gun 21) in order to collect the unused electron beam

4   energy for subsequent use in the system. Such reuse of unused

5   electron beam energy enhances the efficiency of the overall

6   system.

7   The electron beam energy and the RF signal are kept separate

8   from each other. No RF signal is coupled through the beam tunnel

9   hole to the beam collector 27 because the gap (not shown) between

10 the walls (not shown) of the rectangular waveguide 31 is thick

11 enough that the traveling wave of the RF signal does not couple

12 directly through the beam tunnel hole. It should be recalled

13 that the beam tunnel hole is located on the narrow wall of the

14 rectangular waveguide 31, where the RF electric field of the

15 operating TE mode (TE_{10}) is zero. Therefore, the beam tunnel

16 hole can be made larger without distorting the electric field

17 structure, and a high power electron beam with high current can

18 be transmitted through the circuit.

19

20   Fig. 2 is a graph of the dispersion diagram of the folded

21 waveguide gyrotron-traveling-wave-amplifier of Fig. 1. More

22 specifically, Fig. 2 shows that the transverse beam modulation

23 and RF amplification originate from the negative mass instability

24 in the fundamental forward space harmonic of both the "fast" and

1   "slow" wave regions of the dispersion diagram for the folded

2   waveguide gyrotron-traveling-wave-amplifier of Fig. 1.

3   In the graph of Fig. 2, the various symbols can be defined as:

4

5   m = 0   is the 0 space harmonic mode,

6   which is the forward wave.

7   m = 1   is the first space harmonic,

8   which is the backward wave.

9   beam line = the beam cyclotron line.

10   light line = the dotted line.

11   fast wave = anything to the left of the light line.

12   slow wave = anything to the right of the light line.

13

14   In the fast wave region, the phase velocity (v_{ph}) is

15   actually greater than the speed of light (C), as shown in the

16   equation:

17              $$v_{ph} = \omega/k_z > C \qquad\qquad (1)$$

18   That is why it is called a fast wave.

19

20   In the slow wave region, the phase velocity (v_{ph}) is less

21   than the speed of light (C), as shown in the equation:

22              $$v_{ph} = \omega/k_z < C \qquad\qquad (2)$$

23   That is why it is called a slow wave.

24

1   Interaction occurs in the folded waveguide gyrotron-

2   traveling-wave-amplifier of Fig. 1 when the phase velocity of

3   the forward wave (m = 0) is synchronized with the phase velocity

4   of the beam line (beam cyclotron line). As mentioned before, the

5   invention can operate in both of the fast wave and slow wave

6   regions. More specifically, it can operate in the operating

7   region designated by the dashed area 39. Note that this operating

8   region within area 39 covers part of the slow wave region and

9   part of the fast wave region, and that there is continuous

10 interaction across the light line. This is the most important

11 operational difference between the present invention and a

12 conventional gyrotron tube. A conventional gyrotron tube can

13 operate in only one single region - in either the fast wave

14 region or the slow wave region - but not in both regions. This is

15 the fundamental reason why the bandwidth cannot be extended in a

16 prior art or conventional gyrotron tube. In order to extend the

17 bandwidth, it would be necessary to cover parts of both of the

18 fast and slow regions. Otherwise a gain dip will occur near the

19 intersection of the light line, which will cause a discontinuity

20 in the bandwidth.

21   Thus, Fig. 2 shows the phase synchronism between the RF

22 phase velocity and the beam phase velocity and the operating

23 region 39 where the RF phase velocity is synchronized with the

24 beam phase velocity.

1   Fig. 3 is a graph of signal gain versus frequency for the

2   rectangular folded waveguide gyrotron-traveling-wave-amplifier of

3   Fig. 1, using linear theory. From Fig. 3 information can be

4   derived as to the bandwidth and gain that can be obtained from,

5   for example, the folded waveguide gyrotron-traveling-wave-

6   amplifier of Fig. 1. As shown in Fig. 2, the light line crossed

7   at about 36 GHz. Thus, in this particular example, Fig. 3 shows

8   that at 36 GHz the bandwidth is about 15% and the gain is about

9   2.3 dB/cm. Note that there is no discontinuity of gain between

10   the fast wave and the slow wave region, indicating that broadband

11   operation is feasible in the folded waveguide gyrotron-traveling-

12   wave-amplifier of Fig. 1.

13   A 2-1/2 dimensional particle-in-cell, non-linear code, MAGIC

14   has been used to verify the electron negative mass instability in

15   the H-plane bend, rectangular serpentine waveguide of Fig. 1.

16   The MAGIC code was developed by Mission Research corporation,

17   Newington, VA, is well known on the art, and stands for magnet

18   insulation code. This MAGIC code simulates any problem like, for

19   example, an electron beam, an ion beam, an electromagnetic wave,

20   that is involved in a system. It calculates Maxwell equations

21   for electromagnetic properties, for energy exchanges and for

22   other matters. In the folded waveguide gyrotron-traveling-wave-

23   amplifier of Fig. 1, an electron beam and an electromagnetic wave

24   are utilized. The MAGIC code was utilized to look at the

1 nteraction mechanism between the electron beam and the

2 electromagnetic wave. However, due to a code limitation on the

3 number of grids and long simulation times, simulations were

4 performed with a circuit of 20 periods.

5

6 Fig. 4 is a graph of the output obtained from the use of the

7 MAGIC code, showing RF power growth along the axial distance

8 through the interaction circuit of Fig. 1. More particularly,

9 Fig. 4 shows a typical plot of power conversion efficiency versus

10 axial distance where V = 61.5 kV, I = 3 A, α = 1.0, B = 9.8 kG,

11 f = 32.5 GHz, input power = 25W. Simulation showed a saturated

12 efficiency of 22 %, corresponding to high power radiation of ˜ 40

13 kW. Higher RF power extraction from electron beam energy is

14 expected with higher α and increased beam current, and by

15 employing axial magnetic field tapering along the device. It

16 should be noted that efficiency enhancement through magnetic

17 field tapering is not possible with a conventional folded

18 waveguide traveling wave tube.

19

20 Fig. 5 illustrates the equivalent circuit model of the

21 interaction circuit of Fig. 1, representing periodic bends Y_0'

22 and periodic straight sections Y_0 and a inductive shunt

23 susceptance -B of the interaction circuit.

24 When a wave phase in the periodic folded waveguide circuit

1 changes by $n\pi$ where n is an integer number, RF scattering is in

2 phase and adds up along the guide, resulting in a series of

3 bandgaps or stopbands in a frequency domain. Dispersion

4 characteristics and bandgaps have been analyzed by the use of the

5 equivalent circuit model of the interaction circuit 25 of Fig. 1,

6 as shown in Fig. 5. The waveguide bend is modeled as a uniform

7 transmission line with a characteristic admittance Y_0', a

8 inductive shunt susceptance -B, and a guide wavelength $\lambda_{g\phi}$.

9

10 Fig. 6 illustrates plots of numerical solutions of Fig. 5,

11 showing bandgaps near 32.2 GHz and 40.5 GHz. When the RF

12 mismatch near the bandgaps exceeds an amplifier gain in the

13 circuit, the device is subject to oscillations in the mid-band

14 and its bandwidth becomes reduced because there can be no

15 propagation of RF energy across either of the bandgaps without

16 the occurrence of an undesirable RF oscillation in the amplifier.

17 There are several possible ways of avoiding oscillations at the

18 stop-band frequencies; (1) RF reactive loads, (2) ridged

19 serpentine circuit, (3) a multi-stage configuration with the

20 magnetic field detuned and the beam velocity ratio reduced, (4)

21 frequency selective loads, and (5) breaking the structural

22 periodicity by tapering ℓ and h while maintaining the beam-wave

23 resonance with $\ell/(\ell+h)$ unchanged.

1   Fig. 7 shows an exemplary multi-stage amplifier

2   configuration of the amplifier embodiment of Fig. 1 (and also the

3   embodiment of Figs. 10 and 11) of avoiding oscillation at the

4   bandgap frequencies.

5   The multi-stage amplifier configuration of Fig. 7 is

6   comprised of first and second waveguide sections 31A and 31B,

7   respectively. This multi-stage amplifier configuration reduces

8   an amplifier gain in each of the waveguide sections 31A and 31B

9   less than an RF mismatch would. Under this condition, the

10   amplifier configuration of Fig. 7 is not subject to oscillation,

11   and basically operates in the same manner as the amplifier of

12   Fig. 1.

13   In operation, an RF input signal is applied to an input end

14   33A of the first waveguide section 31A. This RF input signal

15   interacts with and modulates an incoming axis-encircling electron

16   beam 23 in just that first waveguide section 31A. The modulated

17   electron beam 23 propagates through the beam channel holes (not

18   shown) into the second waveguide section 31B. The spent RF input

19   signal passes through an RF coupler 38A and is dissipated by an

20   RF load 42A. The RF coupler 38A can be used to sample the spent

21   RF input signal.

22   The modulated electron beam 23 that propagates into the

23   second waveguide section 31B produces or creates an RF signal at

24   a frequency corresponding to the resonance condition of Fig. 2

15

1   (namely at the frequency at which the electron beam was initially

2   modulated in the first waveguide section 31A). The modulated

3   electron beam and the created RF signal interact with each other

4   in the second waveguide section 31B, enabling the created RF

5   signal to be amplified by taking energy from the modulated

6   electron beam that created it until that RF signal reaches

7   saturation. The resultant amplified RF signal is coupled out of

8   an output end 35A of the second waveguide section 31B, while the

9   remaining electron beam energy left after interaction with the

10   amplified RF signal propagates through the beam tunnel hole (not

11   shown) in the second waveguide section 31B to the beam collector

12   27. The beam collector 27 is preferrably a depressed beam

13   collector.

14   Any backward wave from the second waveguide section 31B

15   passes through an RF coupler 38B and is dissipated by an RF load

16   42A. The RF coupler 38B can be used to sample the backward wave.

17

18   The use of a periodic reactive element, or a beam tunnel

19   hole, is another way that the bandgap problem can be cured. The

20   hole is model as a shunt susceptance in the straight waveguide

21   with a characteristic admittance Y_0 and a guide wavelength λ_g is

22   a guide wavelength where the susceptance can be determined.

23   It should be recalled that in Fig. 6 no beam hole was taken

24   into account in providing numerical solutions to the equivalent

1   circuit model of Fig. 5. The Fig. 6 solution to the problem of

2   Fig. 5 only involved the waveguide bends and the bandgaps of Fig.

3   6 came from the periodicity of these waveguide bends.

4

5   Fig. 8 illustrates the effect of a beam tunnel hole on the

6   first bandgap of Fig. 6 and the center frequency shift of the

7   first bandgap from about 32.2 GHz to a lower frequency of about

8   31.5 GHz. As a beam tunnel hole diameter increases, the bandgap

9   gradually decreases. It is interesting to note that the bandgap

10   completely disappears and a mode coalescing of upper and low

11   band-edges takes place near the beam tunnel hole diameter of

12   about 82 mils when the circuit loading elements, inductive and

13   capacitive, cancel out each other. However, further increase of

14   a beam tunnel hole diameter beyond that 82 mil diameter rapidly

15   increases the bandgap because the beam tunnel hole becomes a

16   dominant factor of determining the bandgap.

17

18   In addition to the equivalent circuit calculation of Fig. 5,

19   the MAGIC code is used to examine the effect of the periodic beam

20   tunnel holes on the bandgap. Fig. 9 shows transmission losses of

21   a 12-period folded waveguide gyrotron-traveling-wave-amplifier

22   circuit as a function of frequency for two cases: (a) a circuit

23   with waveguide bends only in the serpentine waveguide 31 (Fig. 1)

24   and (b) a circuit with both bends and beam tunnel holes in the

1   serpentine waveguide 31 where the beam tunnel hole is modeled as

2   a slot equal to the circular hole diameter of 75 mils.

3   The solid line in Fig. 9 is the case with bends only and

4   shows a bandgap at about 33 GHz. In Fig. 6, this bandgap was

5   predicted at about 32.5 GHz. Therefore, Fig. 9 is quite

6   consistent with Fig. 6 as to this bandgap at 32.5 or 33 GHz.

7   The dashed line in Fig. 9 is the case with both bends and

8   beam tunnel holes in the interaction circuit 25 of Fig. 1. With

9   both bends and beam tunnel holes in the interaction circuit 25

10   the bandgap frequency shifts downward to a lower frequency and a

11   better RF transmission is observed when the beam hole is taken

12   into account in the circuit simulation. Thus, both the

13   equivalent circuit model of Fig. 5 and the computer simulation

14   code of Fig. 9 produce qualitative agreement on the transmission

15   loss at about 32.5 GHz. In addition, both of them reach

16   qualitative agreement on the coalescing of the bandgap at about

17   80 mils.

18   Note, as shown in Fig. 8, that a 1.6% bandgap is produced

19   when there is no beam tunnel hole, whereas that 1.6% bandgap is

20   reduced to zero when an 82 mil beam tunnel hole is utilized. This

21   is a substantial improvement compared to no beam tunnel hole.

22   With a proper choice of a beam hole diameter, it is possible to

23   eliminate the first bandgap at about 32.5 GHz (Fig, 6) and avoid

24   oscillations in experiments.

1   Another approach to avoiding that first bandgap and its

2   associated bandgap oscillations is by replacing the folded

3   rectangular serpentine waveguide 31 in Fig. 1 with a double-

4   ridged transverse electric folded waveguide structure, which is

5   shown in Figs. 10 and 11. Fig. 10 illustrates a double-ridged,

6   transverse electric, folded waveguide 40 used in place of the

7   folded rectangular serpentine waveguide 31 of Fig. 1 in a second

8   embodiment of the invention; and Fig. 11 illustrates a cross-

9   sectional view of the double-ridged, transverse electric, folded

10 waveguide 40 of Fig. 10. Figs. 10 and 11 show metal ridges 41 in

11 the double-ridged waveguide 40. In Fig. 11, note that the

12 electric field line 43 is pointing up like that of the TE10 mode.

13 The electron beam passes through the beam hole 36 and interacts

14 with the transverse electric field injected from the input end

15 33B of the waveguide 40. Amplified RF is extracted from the

16 output end 35B.

17   The ridged waveguide 40 of Figs. 10 and 11 has the same

18 cutoff frequency and dispersion characteristics as the

19 rectangular waveguide of Fig. 1. However, one important

20 difference between the double-ridged waveguide 40 and the

21 rectangular waveguide 31 of Fig. 1 is that the width of the

22 double-ridged waveguide 40 is almost half of that of the

23 rectangular waveguide 31. Therefore, the double-ridged waveguide

24 configuration increases the spacing of the space harmonics and

1 reduces the gap detuning angle compared with rectangular H-plane

2 bend folded guide.

3 With the width of the double-ridged waveguide 40 reduced by

4 almost a factor of 2, the frequency of the first bandgap, which

5 is about 32. 5 GHz for the standard folded waveguide (as shown in

6 Fig. 6), is shifted up and away from the operating frequency

7 range to around 39 GHz for the case of a double-ridged folded

8 waveguide.

9

10 Fig. 12 is a graph of signal gain versus frequency for the

11 double-ridged, transverse electric, folded waveguide of Figs. 10

12 and 11. Again, linear theory is used to derive the waveforms

13 shown in Fig. 12 for actual velocity spreads of 0%, 1%, 2%, 3%

14 and 4% included in the MAGIC code. Linear theory for the ridged

15 configuration predicts a gain of 2.5 -3 dB/cm and an

16 instantaneous bandwidth of 15% - 30% for V = 65 kV, I = 3 A axis-

17 encircling electron beam having a velocity ratio of α = 0.8.

18 As shown in Fig. 12, the bandwidth and gain of the device

19 decrease as beam axial velocity spread increases. An advanced

20 center post electron gun producing a high quality electron beam

21 with low axial velocity spread ($\Delta v_z/v_z$ < 2%) is available for use

22 with the double-ridged, transverse electric, folded waveguide of

23 Figs. 10 and 11 to minimize beam axial velocity spread increases

24 and thereby maximize the gain and bandwidth of the device.

1   Fig. 13 illustrates a low-gain, single-stage, 35 GHz test

2 device 45 (12 periods) having a rectangular cross-section. The

3 test device 45 is similar to the rectangular folded waveguide 31

4 of Fig. 1. This test device 45 was fabricated using low-cost

5 wire electric-discharge-machining (EDM) technology and includes a

6 center piece 47 and two end portions 49 and 51.

7   The center piece 47 contains the 12-period configuration 48

8 of the H-plane bend rectangular waveguide 31 of Fig. 1 and the

9 end portions 49 and 51 furnish the adjacent sides of the

10 rectangular waveguide 31. End portion 49 contains alignment holes

11 53A and 55A; end portion 51 contains alignment holes 53B and 55B;

12 and center piece 47 contains alignment holes 53C and 55C , as

13 well as a sequence of beam tunnel holes 66.

14   In assembling the test device 45, the center piece 47 is

15 sandwiched between the end portions 49 and 51 with the holes 53A,

16 53C and 53B being aligned with each other at one end of the

17 assembled test device 45, and the holes 55A, 55C and 55B being

18 aligned with each other at the other end of the assembled test

19 device 45. After the test device 45 is assembled, the RF input

20 and RF output are cut out of the test device 45 and a magnet (not

21 shown) is disposed around the test device 45 to provide an

22 exemplary one Tesla solenoid magnetic field to the device 45.

1   Fig. 14 shows the return loss (or reflected RF

2   electromagnetic power) that was measured from the test device 45

3   of Fig. 13 as a function of frequency under different conditions.

4   Four complete trace lines are shown in Fig. 14. The thin solid

5   line 57 is for a beam tunnel hole diameter of 70 mils; the dotted

6   line 59 is for a beam tunnel hole of 80 mils; the long dashed

7   line 61 is for a beam tunnel hole of 90 mils; and the thick

8   solid line 63 is for a beam tunnel hole of 90 mils and with

9   impedance matching pins. Exemplary values along the vertical

10   return loss (dB) axis of Fig. 14 mean: 0 dB means 100%

11   reflection; -10 dB means 10% reflection; -20 dB means 1%

12   reflection; -30 dB means .1% reflection; and so forth.

13   The beam hole loading effect of the test device 45 of Fig.

14   13 was tested by changing the beam tunnel hole size. As shown in

15   Figure 14, as the beam hole diameter increases to 90 mils, the

16   return loss becomes better and the bandgap at ˜ 32 GHz becomes

17   narrower. However there is a limit as to how large the beam

18   tunnel hole can be made. So instead of changing the size of the

19   beam tunnel hole, impedance matching pins can be utilized to

20   match the impedances along the rectangular serpentine waveguide.

21   Such use of impedance matching pins to change the impedance of

22   the rectangular waveguide corresponds to making the beam tunnel

23   hole larger (or smaller).

1   With a series of impedance matching or tuning pins on the

2   waveguide bends and near the beam holes, a return loss at the

3   bandgap frequency becomes better than -10 dB (see the thick

4   solid line 63 in Figure 14). This indicates that, by introducing

5   a proper reactive element in the circuit, the bandgap can be

6   completely eliminated and an operating bandwidth can be extended

7   across the bandgap without oscillations. The measured frequency

8   shift toward a low frequency as the beam tunnel hole diameter

9   increases consists of the predictions by both the equivalent

10   circuit model calculations and MAGIC simulations. An excellent

11   return loss of less than -15 dB has been measured over the Ka-

12   band frequency range (32 - 39 GHz).

13

14   Fig. 15 is a schematic diagram of a folded waveguide

15   gyrotron oscillator in a third embodiment of the invention. In

16   this third embodiment, the invention could be operated as an

17   oscillator without the use of an external RF input signal. When

18   the beam velocity is sychronized with a negative group velocity

19   of a higher space harmonic mode, a strong instability takes place

20   and a high power RF is extracted through the input side of the

21   serpentine waveguide 31.

22   In the oscillator embodiment of Fig. 15, there is no RF

23   input to the waveguide 31, and the interaction circuit 25 is

24   responsive to the axis-encircling electron beam for developing an

1   RF signal. If that RF signal is a backward wave, it is outputted

2   from the first end 33 of the interaction circuit 25. On the other

3   hand, if that RF signal is a forward wave, it is outputted from

4   the second end 35 of the interaction circuit 25.   In the

5   oscillator configuration, the operating frequency is tunable by

6   adjusting the external magnetic field and beam voltage.

7

8   The folded waveguide gyrotron-traveling-wave-

9   amplifier/folded waveguide gyrotron oscillator can be operated at

10 a high beam cyclotron harmonic. With the high beam cyclotron

11 harmonic operation, the required external magnetic field is

12 reduced by a factor of the harmonic number.

13   Potential advantages of the folded waveguide gyrotron-

14 traveling-wave-amplifier/folded waveguide gyrotron oscillator of

15 the invention over various other prior art broadband gyrotron-

16 traveling-wave-amplifier devices, such as the tapered fast wave

17 gyrotron-traveling-wave-tube and the dielectric loaded slow wave

18 cyclotron amplifier (SWCA), include: compactness, robustness,

19 ease of fabrication, low cost, broadband metallic circuit, broad

20 bandwidth due to no gain discontinuity across the light line,

21 simplicity of coupling and circuit severing, natural separation

22 of beam and RF applicable for depressed collector operation, high

23 power handling capability, and low magnetic field operation.

1   The folded waveguide gyrotron-traveling-wave-

2   amplifier/folded waveguide gyrotron oscillator circuit of the

3   invention has additional advantages over the conventional E-plane

4   bend, folded waveguide traveling-wave-tube including: larger beam

5   tunnel for high power beam injection with little distortion of

6   waveguide field structure, easy mode coalescing by adjusting a

7   beam hole diameter, higher efficiency and therefore increased

8   output power through the use of magnetic field tapering, and

9   fundamental forward space harmonic operation.

10

11   Therefore, what has been described are a folded waveguide,

12   gyrotron-traveling-wave-amplifier capable of producing high

13   power, broadband millimeter wave radiation in preferred

14   embodiments of the invention and a folded waveguide gyrotron

15   oscillator in another preferred embodiment of the invention.

16

17   While the invention has been illustrated and described in

18   detail in the drawings and foregoing description, it should

19   readily be understood that many modifications and variations of

20   the present invention are possible within the purview of the

21   claimed invention. It is therefore to be understood that, within

22   the scope of the appended claims, the invention may be practiced

23   otherwise than as specifically described.

ABSTRACT

A folded waveguide gyrotron-traveling-wave-amplifier comprises: an electron gun for transmitting an axis-encircling beam of electrons with large transverse energy along a first path having an axis; an RF source for producing and applying in a second path an RF input millimeter wave signal having a bandwidth in a preselected frequency domain and having a transverse electric field; a source for generating a solenoid magnetic field parallel to the axis along the first path; a beam collector; and an interaction circuit such as an H-plane bend serpentine waveguide positioned within the solenoid magnetic field and having a narrow wall containing a beam tunnel hole for passing the axis-encircling beam of electrons therethrough to the beam collector, an output end, and an input end for receiving and passing the RF input millimeter wave signal through the H-plane bend serpentine waveguide to the output end to modulate the axis-encircling electron beam, the modulated axis-encircling electron beam amplifying the RF input signal and also broadening the instantaneous bandwidth of the amplified RF input signal through the negative mass instability in the fundamental forward space harmonic of both fast and slow wave regions in the preselected frequency domain. In a second embodiment, a double-ridged TE folded waveguide is used in place of the H-plane bend serpentine waveguide. In a third embodiment, there is no RF input signal and the interaction circuit generates an RF signal which is outputted from one of the input and output ends.
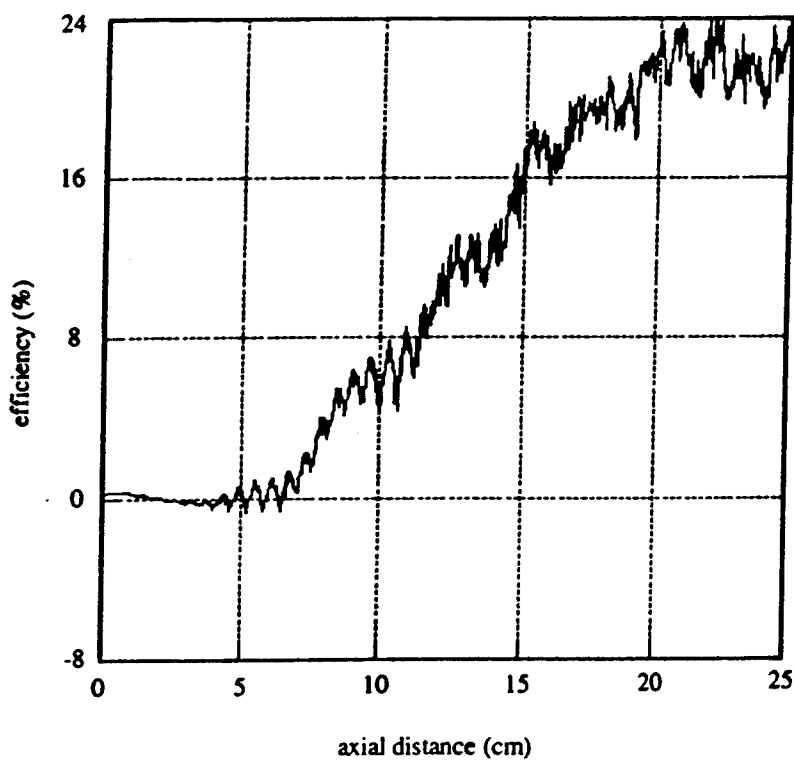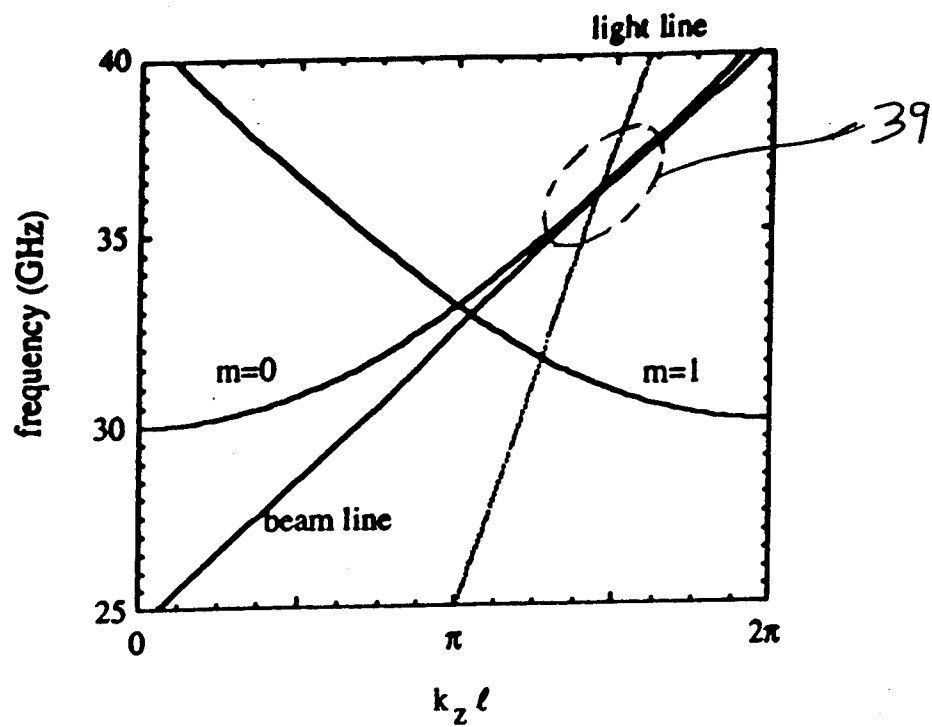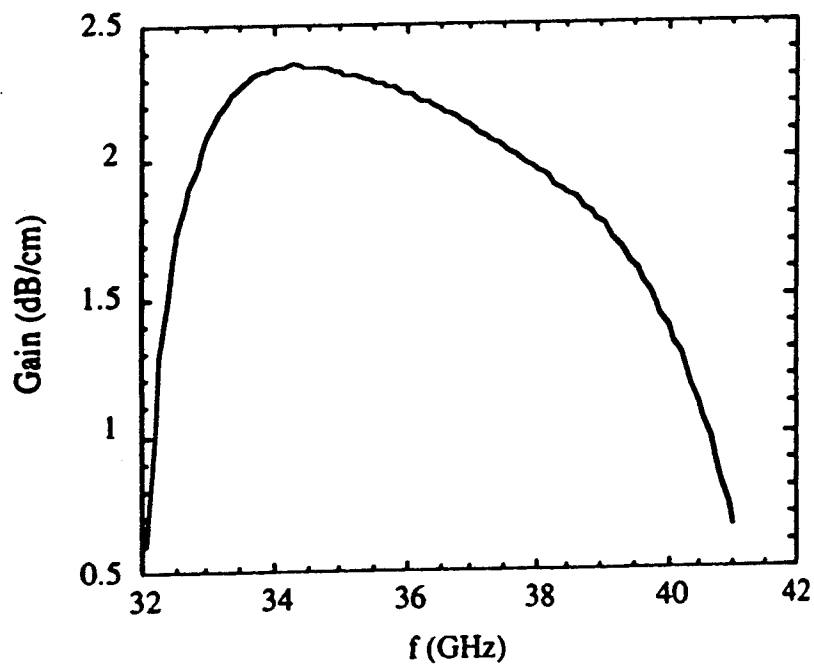
axis-encircling
beam 23

H-plane bend
rectangular waveguide 31

magnet 29

RF out

35

27

37

b

21

RF in

33

ℓ

beam collector

electron gun

interaction circuit 25

collector

FIG. 1

24

16

efficiency (%)

8

0

-8

0   5   10   15   20   25

axial distance (cm)

FIG. 4

FIG. 2

FIG. 3

γ_0 -B γ_0 -B γ_0 -B γ_0 -B γ_0

bend   straight   bend   straight   bend

FIG. 5

2nd bandgap

1st bandgap

frequency (GHz)

$k_z \ell$

FIG. 6

AXIS-ENCIRCLING
BEAM 23

RF INPUT

33A

31A

RF
COUPLER
38B

RF LOAD 42B

RF
COUPLER 38A

RF LOAD 42A

31B

AMPLIFIED
RF OUTPUT

35A

27

BEAM
COLLECTOR

FIG. 7

FIG. 8

FIG. 9

41

40

36

35B

33B

41

36

FIG. 10

electric field 43
of TE10 mode

metal ridge 41

beam

metal ridge 41

FIG. 11

FIG. 12

FIG. 13

FIG. 14

FIG. 15